

## NEW STUDIES OF MARTIAN VOLCANOES

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To investigate the morphology, topography and evolution of volcanic constructs on Mars, we have been studying the volcanoes Olympus Mons, Tyrrhena Patera, and Apollinaris Patera. These studies have relied upon the analysis of digital Viking Orbiter images to measure the depth and slopes of the summit area of Olympus Mons (1), new Earth-based radar measurements for the analysis of the slopes of Tyrrhena Patera (2), and the color characteristics of the flanks of Apollinaris Patera (3).

## OLYMPUS MONS

In order to constrain the sequence of collapse events and subsequent tectonic deformation of the summit caldera of Olympus Mons, we have made a series of height and slope measurements for the summit of the volcano using digital Viking Orbiter images. The highest resolution images (~12 m/pixel) show that the circumferential graben and circumferential ridges within the caldera parallel the contours derived by Wu et al. (4), and that the circumferential ridges in the main crater (Crater #1; ref. 5) are located at a slight break in slope on the eastern part of the caldera floor. The linear ridges that are common on the floors of the younger craters (Craters 4 and 5; ref. 5) are absent from the topographically higher parts of the caldera floor (i.e., areas that exceed an elevation of 23.8 km). With respect to the rim of the caldera, there are azimuthal variations in slope stability, which we interpret to be an indication either of variations in rock strength or areas of localized stress. On the northwest and southeast rims, block faulting has taken place on walls that are less than 1,000 m high, while the southern rim of Crater 6 (ref. 5) is over 3,000 m high and yet the wall rocks show no signs of incipient failure.

In earlier studies (5, 6) we identified both compressional and extensional features on the floor of the Olympus Mons caldera. Our recent topographic measurements show that compressional features include broad (1 - 3 km wide) ridges that are morphologically similar to wrinkle ridges on the Moon and narrower (< 1 km width) linear ridges that are approximately circumferential to the perimeter of Crater 1. A topographic profile across one of the larger wrinkle ridges on the floor of Crater #5 shows that it is > 300 m high on its eastern side and 2 km wide. Typical planar dimensions for the wrinkle ridges on the floor of Craters 1 and 5 are 0.8 - 1.4 km width and 3 - 15 km in length. Maximum dimensions for the largest ridge are 1.8 km width and 23.0 km length.

An extensive series of graben around the perimeter of Crater 1 are the primary extensional features found within the caldera, although additional narrow fractures can be seen both on the caldera floor and upon the rim. We are confident that these features are indeed graben because of their symmetrical geometry (two bounding faults), flat floors, and approximately constant width. Shadow length measurements (from frame 473S28) show that the larger of these graben are ~420 - 450 m wide, may extend for more than 25 km in length, and ~180 - 200 m deep. The smaller fractures are typically 100 m in width, < 5 km in length, and are too shallow for us to confidently determine their depths at an image resolution of ~15 m/pixel.

Within Craters 4 and 5 there are numerous narrow sinuous ridges. These sinuous ridges are typically < 100 m wide, < 5 km in length, and are sufficiently low that their heights cannot be measured from their shadow lengths (i.e., they are probably <~20 m high). Sinuous ridges appear to be superimposed upon the wrinkle ridges, and often traverse the crater floor, a wrinkle ridge, and back to the crater floor without changing their orientation. The small size and their superimposition upon the broader wrinkle ridges suggests to us that these narrow sinuous ridges are older features than the wrinkle ridges, because otherwise their orientations and locations would have been constrained by the wrinkle ridges. We interpret the wrinkle ridges to be the products of compression during the subsidence of the entire caldera floor, and the narrow

sinuous ridges to be constructional features produced when an individual segment of the caldera floor was forming, perhaps analogous to pressure ridges that form on the surface of terrestrial lava lakes (7). Several irregular collapse pits and sinuous troughs can also be found on the floor of Crater 5, and these features may also have formed during the solidification of the surface of a lava lake by localized draining of the near-surface magma (we have observed comparable features on the surface of the September 1982 Kilauea lava flow, Hawaii, where drain-back into the vent followed the termination of activity, and left several irregular-shaped pits at the surface).

#### TYRRHENA PATERA

Tyrrhena Patera (21.5°S, 253.2°W) is one of several heavily dissected volcanoes in the southern highlands of Mars (8). Recent geologic mapping (9) has confirmed that it is a broad volcano possibly composed of four or five principal units, the oldest and most extensive of which are thought to be ash units on the basis of their morphology and erosional characteristics. Tyrrhena Patera represents the earliest central vent volcanism identified on Mars and may reflect a transition from flood-style eruptions which dominated early Martian history.

Because the currently favored models for the formation of the flank units on Tyrrhena Patera involve the emplacement of gravity-driven pyroclastic flows (9), we have taken advantage of the 1988 Mars Opposition to collect new Earth-based radar topographic data for Tyrrhena Patera in order to help refine our knowledge of the volcano's height and slope characteristics. Between August 30th - November 13th 1988, one of us (SHZ) collaborated with the JPL Radar Group and collected seven new topographic profiles between 20.0° - 25.1°S using the Goldstone, CA, radar system (2). Data were collected at X-band (3 cm) and S-band (12 cm), and were obtained at latitudes 20.0°, 20.2°, 20.7°, 21.7°, 21.9°, 22.3°, 22.4° and 25.1°S. These radar profiles augment the topographic information obtained by Downs et al. (10) in 1971 and 1973, which were located at 17.26°, 18.19°, 18.33°, 19.82° and 20.40°S.

The radar data show that the maximum height of Tyrrhena Patera to be 4.71 km above the 6.1 mb datum at 21.9°S (2). Slopes for the upper flanks of the volcano are ~1.18° for ~40 km east of the summit, and 0.64° for ~60 km west of the summit. The eastern basal plain surrounding the volcano is ~400 m lower in altitude than the plain surrounding the western side of the volcano: ~3,100 m above datum compared to 3,500 m above datum. The maximum height variation as one ascends the volcano is 1.5 km along a profile at 21.9°S between 250 - 254°W. This gives an average flank slope of 0.43° over a distance of 220 km. To the west of the summit, the change in elevation is 1.05 km over 220 km (average slope 0.30°) between 254 - 258°W. The volcano has an inferred height-to-basal diameter ratio of ~0.003.

North and south of the volcano, the ridged plains materials of Hesperia Planum are almost flat at a mean elevation of ~3,250 m to the north (at 18.19°S) and 2,900 m to the south (at 25.1°S). This means that the north-south gradient from the volcano summit to the north is 0.42°, and 0.60° from the summit to the south. These values can be compared directly to two slope estimates of Greeley and Crown (ref. 9; their slope "C", which they estimate to be 0.21° and we measure to be 0.42°, and their slope "D", which was estimated to be 0.37° and we measure as 0.60°). We can also approximate the measurement of slope "F" (ref. 9), which was estimated to be 0.19° and is indicated by the radar data to be 0.21°. The steepest slope measured is 3.03° for a 13 km segment of the northern flanks. These radar-derived slopes compare to the 0.09° - 0.37° slopes estimated for Tyrrhena Patera over distances varying from 304 - 634 km (9), and our photoclinometric measurements of  $3.6^\circ \pm 0.5^\circ$  for the maximum slope (11).

#### APOLLINARIS PATERA

In addition to the topographic studies of Martian volcanoes, we have also started detailed analysis of the color data for certain volcanoes, which we hope will yield further information regarding their surface properties. For instance, our preliminary analysis of 3 color and 5 monochrome images of Apollinaris Patera (3), shows that the northern summit of the volcano

has very unusual surface deposits, in the form of temporally-variable high albedo deposits. The spectral behavior of the Apollinaris spot is quite unusual, in that the spot is seen over a long period of time (9/16/76 - 7/7/80), but is variable over a short time period (seen 2/16/78, not seen 3/14/78, seen 3/18/78), and is not correlated with season (Ls). Calibrated Viking Orbiter color data permit a plot of red vs. violet DN values to be constructed (3), and this information indicates that the spot becomes darker at a slower rate than the adjacent terrains for increasingly larger phase angles. Most intriguing is the color shift relative to the rest of the area; the violet radiance of the spot relative to the volcanics changes such that the spot has a lower radiance than the surrounding volcanics at lower phase and a higher radiance at higher phase. We have conducted preliminary investigations of the possible physical character of this albedo feature on the rim of Apollinaris, and consider that an origin either due to unusual composition or photometry is possible (3). Clouds and/or meteorology may also be possible, but the longevity and consistent shape when observed makes this idea less favorable. More significantly, the spot is relatively red, whereas the clouds and fog are blue relative to the rest of the Martian surface. Part of our current effort is designed to further investigate both the temporal variability of this Apollinaris Patera deposit, and to consider the possible role that viewing geometry may have played in the origin of this time-variable feature. We hope that in subsequent years, where appropriate color data exist, we will search for comparable features elsewhere on the planet.

#### FUTURE WORK

Our future studies of Martian volcanoes will place emphasis on the geologic evolution of the volcanoes based upon the combination of photoclinometrically derived topography and analysis of the Viking Orbiter images. For example, from our limited analysis to date (2), there does not appear to be a correlation between the degree of dissection of the flanks of the Tyrrhena Patera and the local slopes. This is somewhat surprising, if either of the two most plausible models for their formation (the channels were carved either by pyroclastic flows (9) or by sapping processes (12)) are valid, because we would expect erosion to have been greatest on the steepest slopes. One of our objectives for the study will therefore be to combine the radar-derived slope information with our photoclinometric profiles to better understand the erosional processes that have shaped the Martian highland patera. We hope to be able to assess whether the larger valleys formed on steeper slopes or whether they were the result of unusually large volume eruptions. Photoclinometry and parallax measurements will, in fact, be the only methods by which topographic information can be derived for some of the other small Martian volcanoes that possess channelized flanks (such as Hecates Tholus, Hadriaca Patera, and Ceraunius Tholus) because these volcanoes lie poleward of the radar ground tracks.

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